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Giffin et al.

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(45) **Date of Patent: Apr. 29, 2014**

(54) **COUNTER-ROTATABLE FAN GAS TURBINE ENGINE WITH AXIAL FLOW POSITIVE DISPLACEMENT WORM GAS GENERATOR**

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F01C 1/107 (2006.01)

(52) **U.S. Cl.**
USPC **415/62**; 416/177

(58) **Field of Classification Search**
USPC .... 60/39.43, 39.162, 45, 226.1, 268, 60/39.45; 415/62, 65, 62.65; 416/124, 416/128, 175, 177, 198 R
See application file for complete search history.

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Primary Examiner — Edward Landrum
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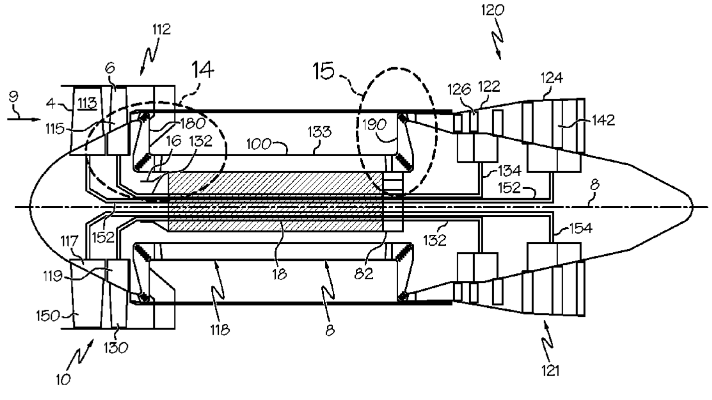
(57) **ABSTRACT**

A counter-rotatable fan turbine engine includes a counter-rotatable fan section, a worm gas generator, and a low pressure turbine to power the counter-rotatable fan section. The low pressure turbine maybe counter-rotatable or have a single direction of rotation in which case it powers the counter-rotatable fan section through a gearbox. The gas generator has inner and outer bodies having offset inner and outer axes extending through first, second, and third sections of a core assembly. At least one of the bodies is rotatable about its axis. The inner and outer bodies have intermeshed inner and outer helical blades wound about the inner and outer axes and extending radially outwardly and inwardly respectively. The helical blades have first, second, and third twist slopes in the first, second, and third sections respectively. A combustor section extends through at least a portion of the second section.

60 Claims, 15 Drawing Sheets



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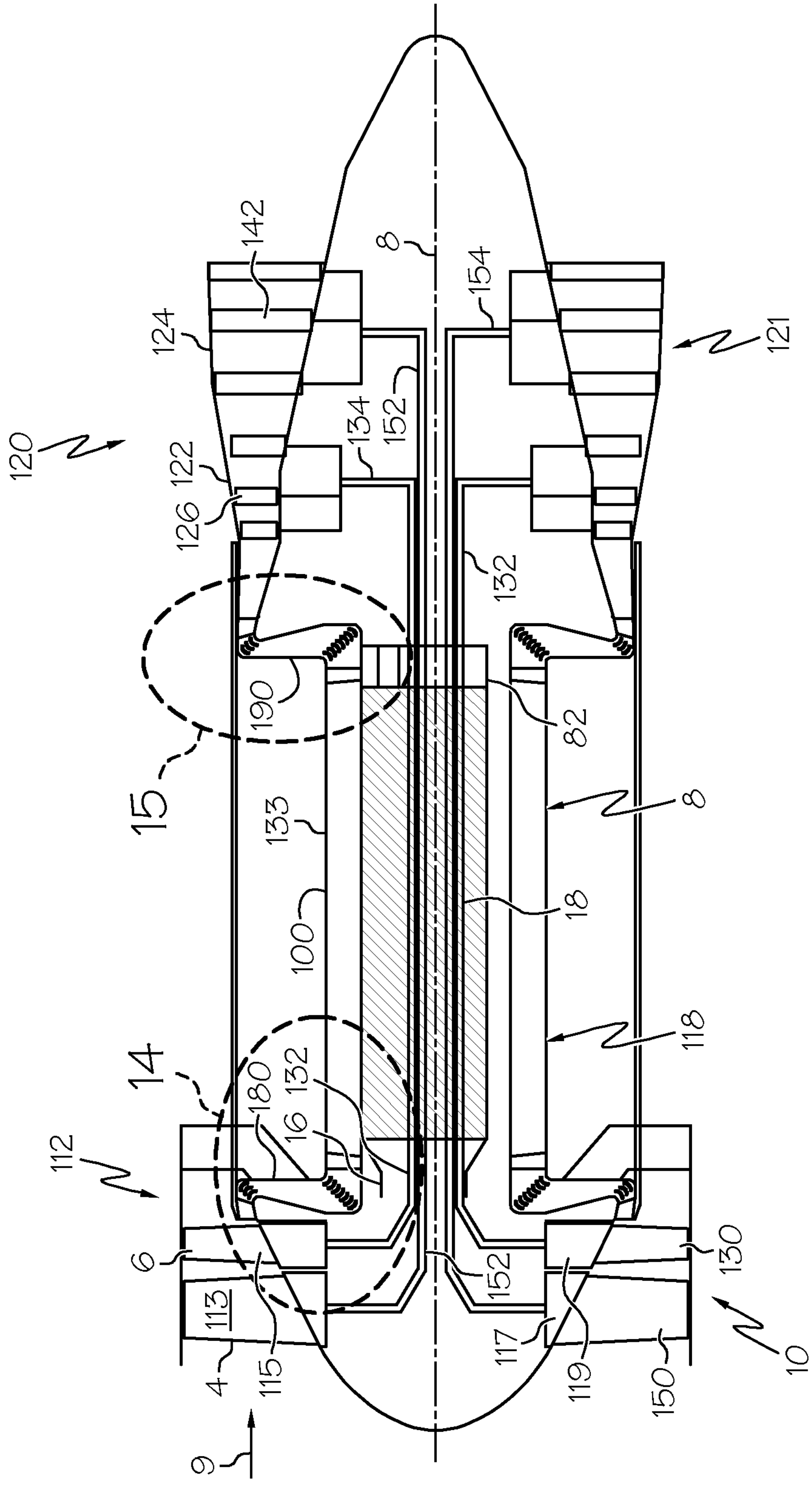

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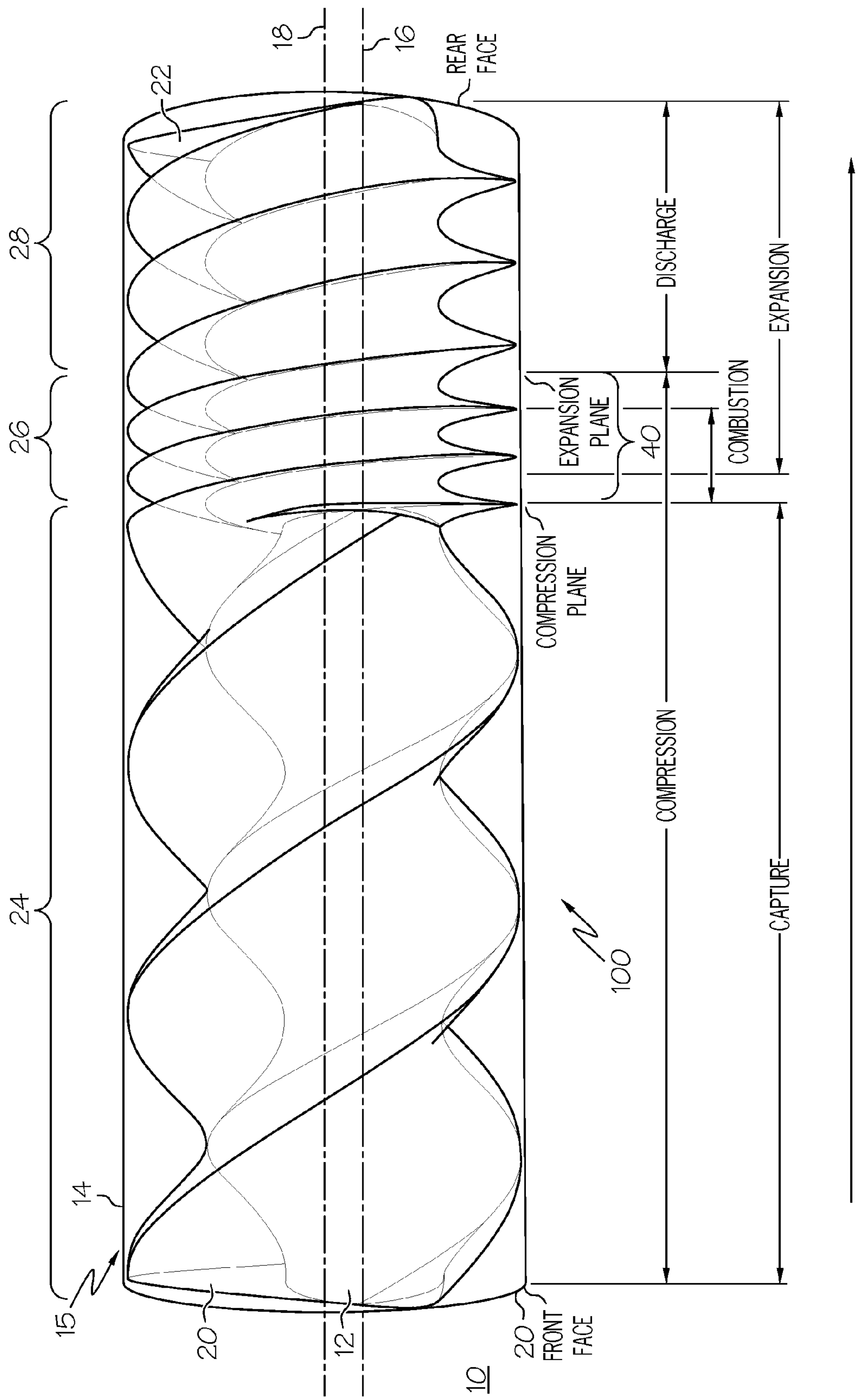
FIG. 1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16
REAR FACE
22
28
26
24
DISCHARGE
EXPANSION
EXPANSION PLANE
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COMBUSTION
COMPRESSION PLANE
COMPRESSION
CAPTURE
100
14
15
20
12
20
FRONT FACE
10

FIG. 2

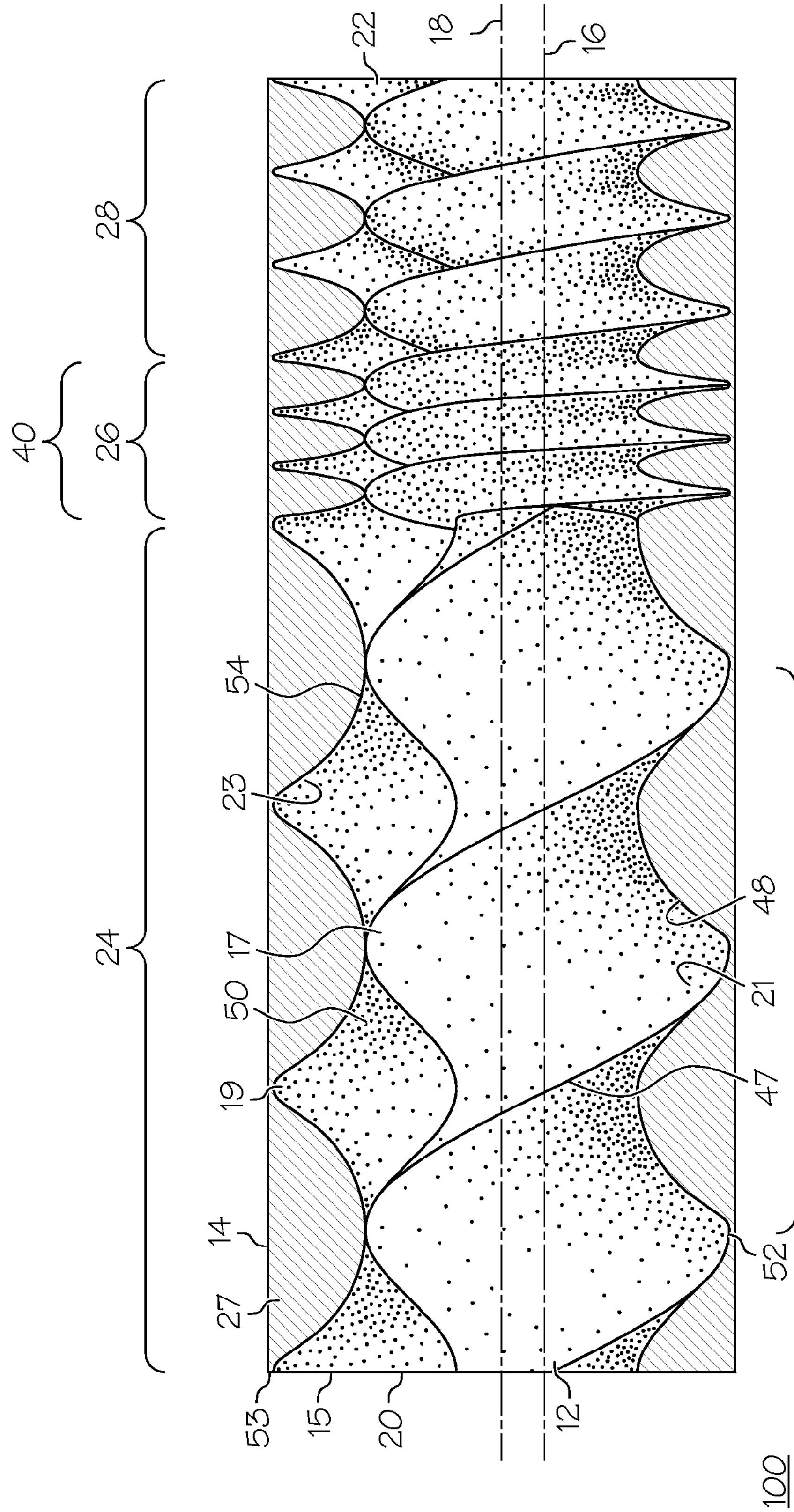
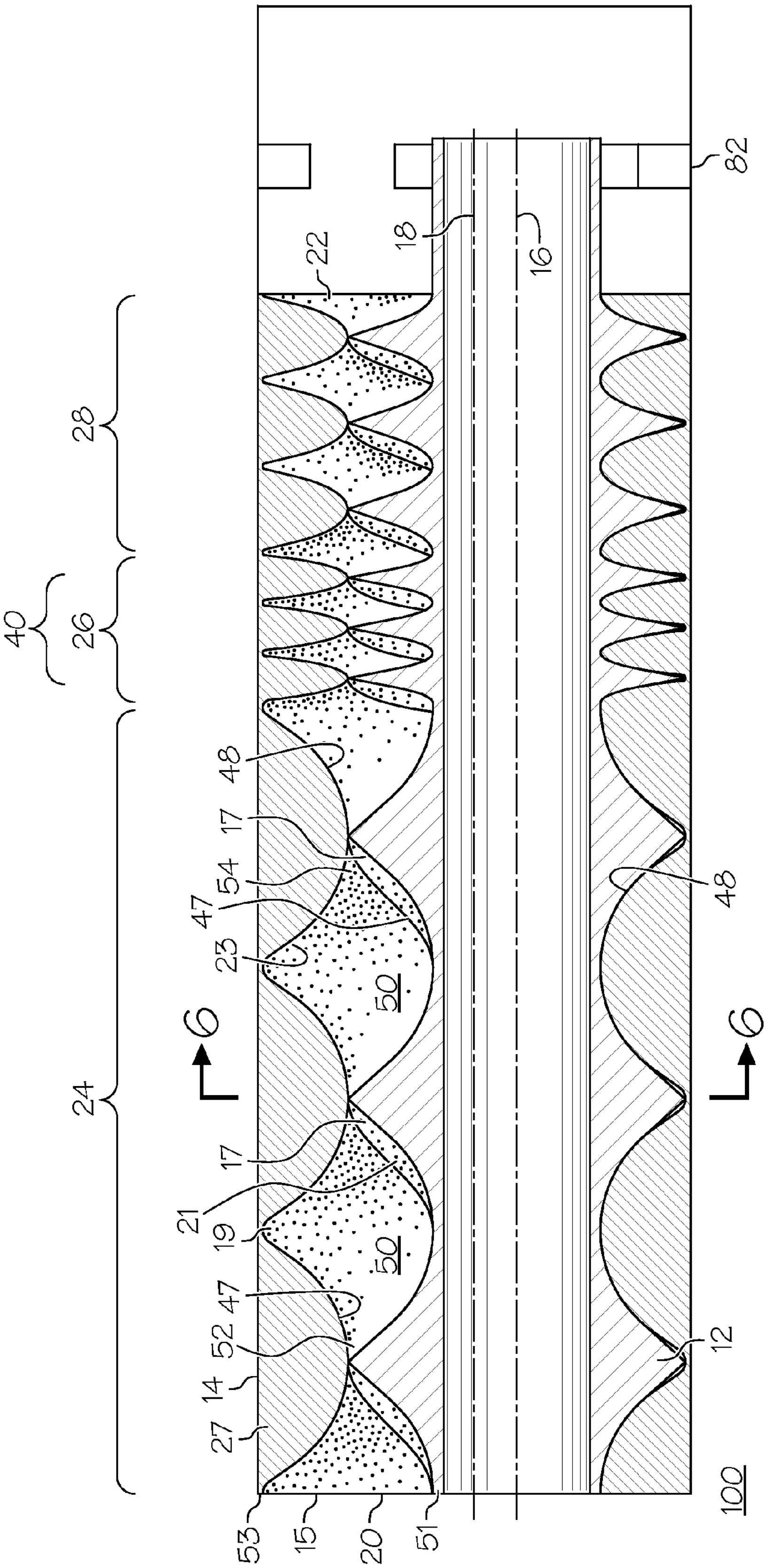


FIG. 3



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20
51
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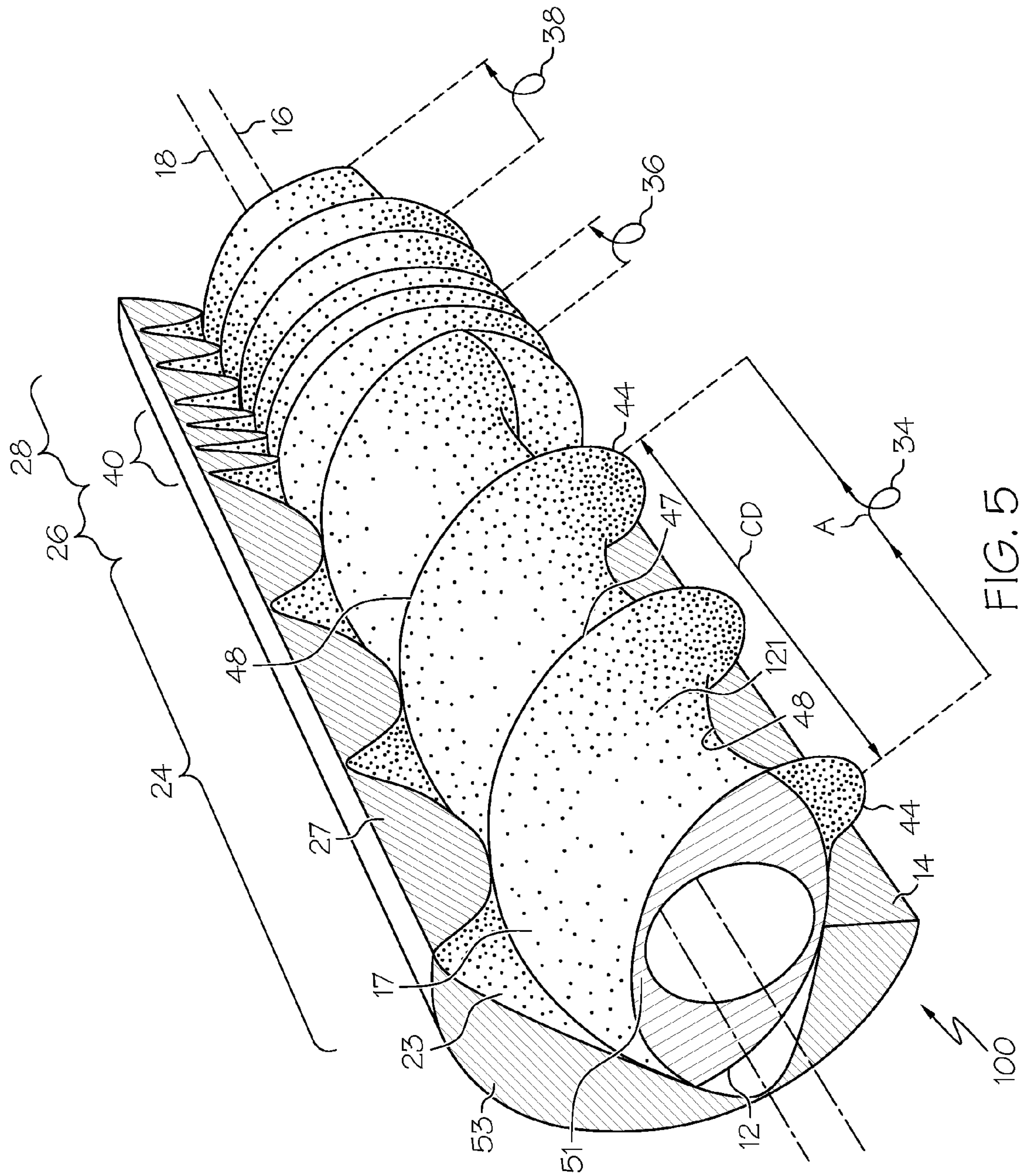
12
100
6

FIG. 4


38
36
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28
40
26
44
34
A
CD
47
48
121
48
24
27
44
14
17
23
100
53
51
12

FIG. 5

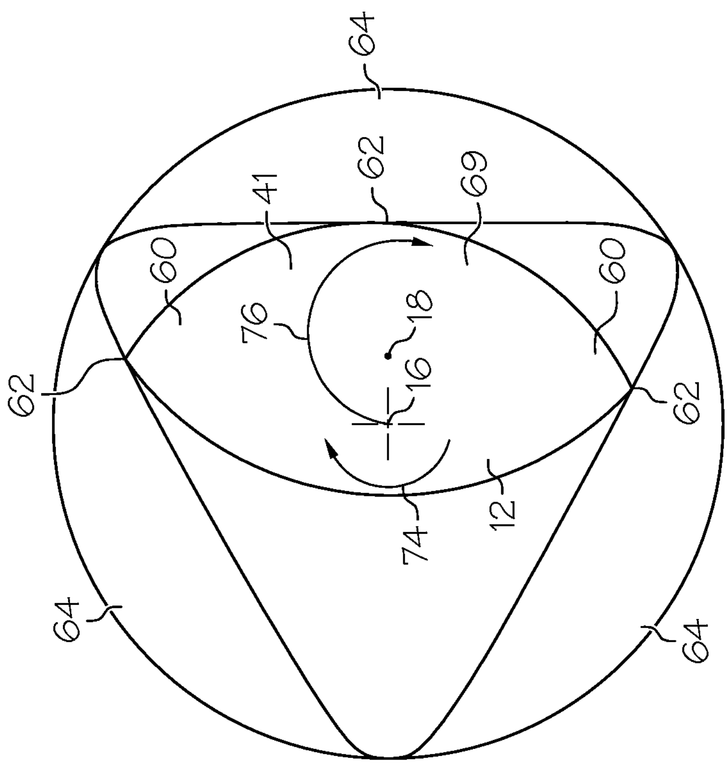


FIG. 6

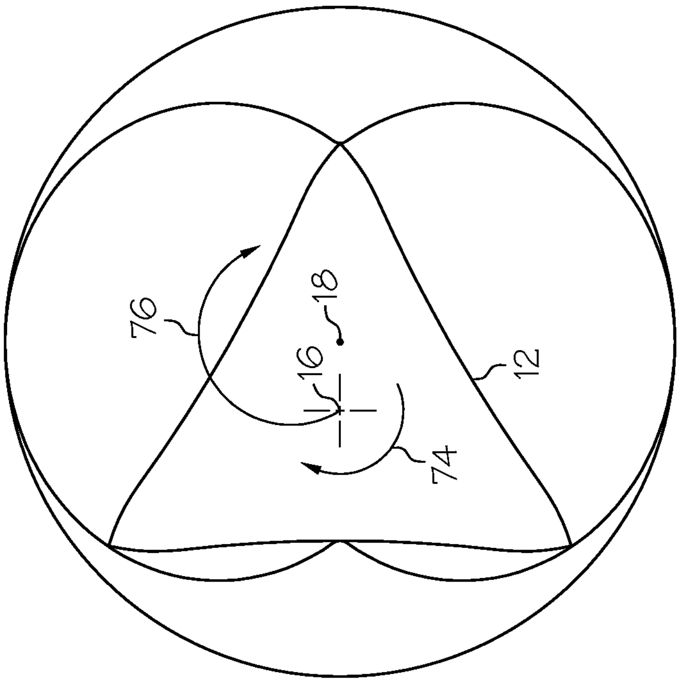


FIG. 8

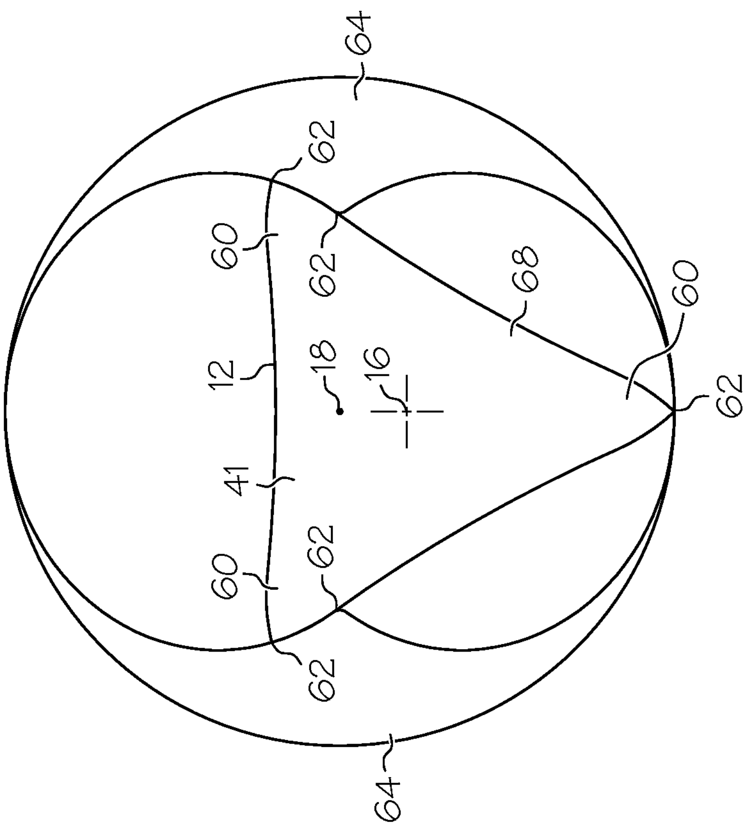


FIG. 7

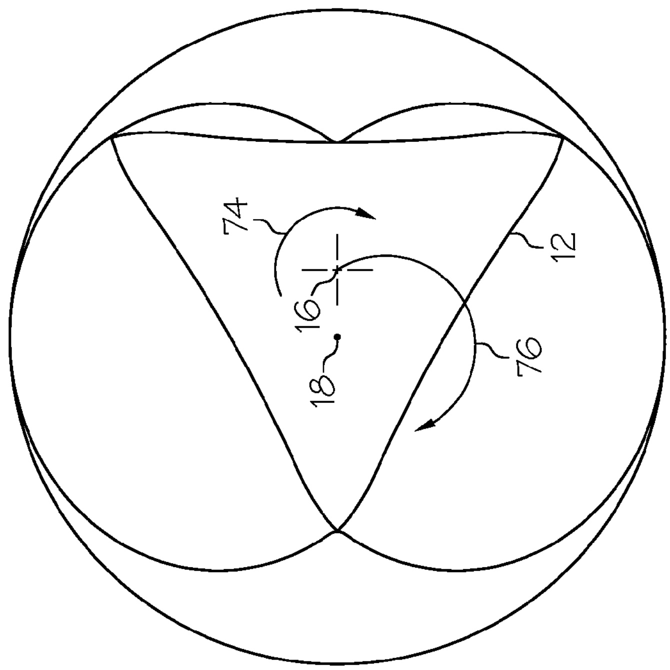


FIG. 10

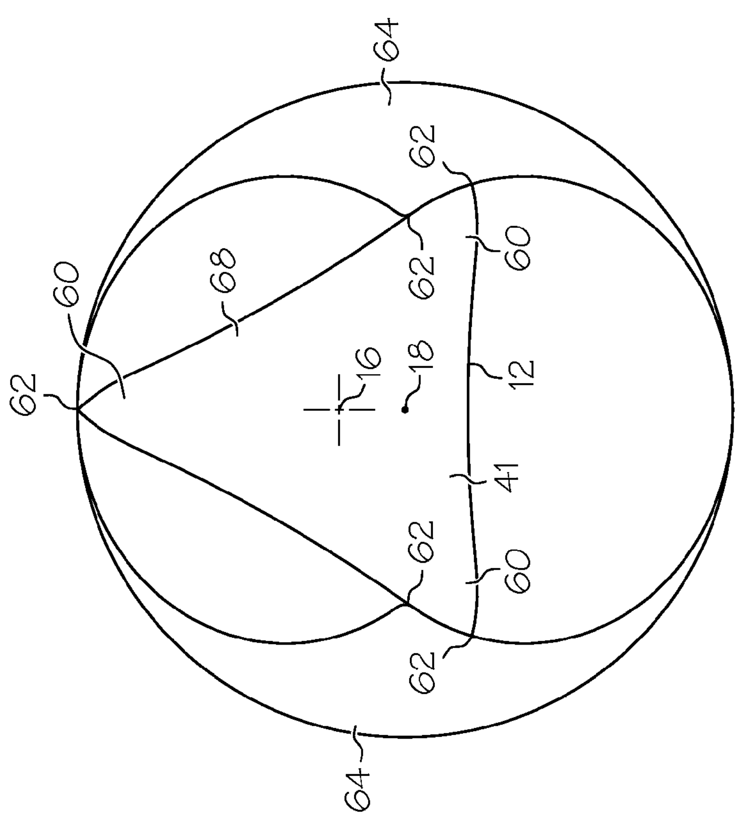


FIG. 9

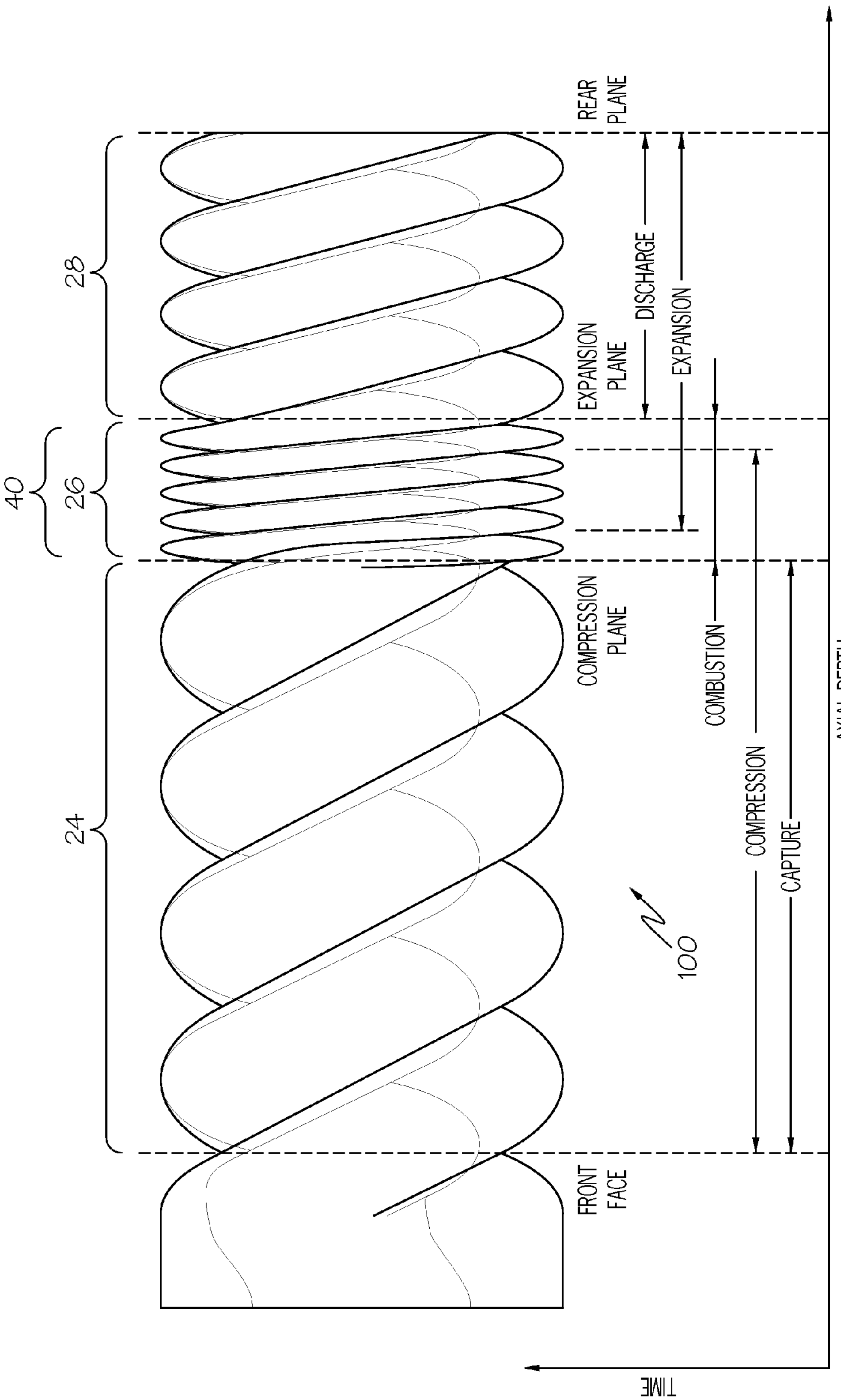
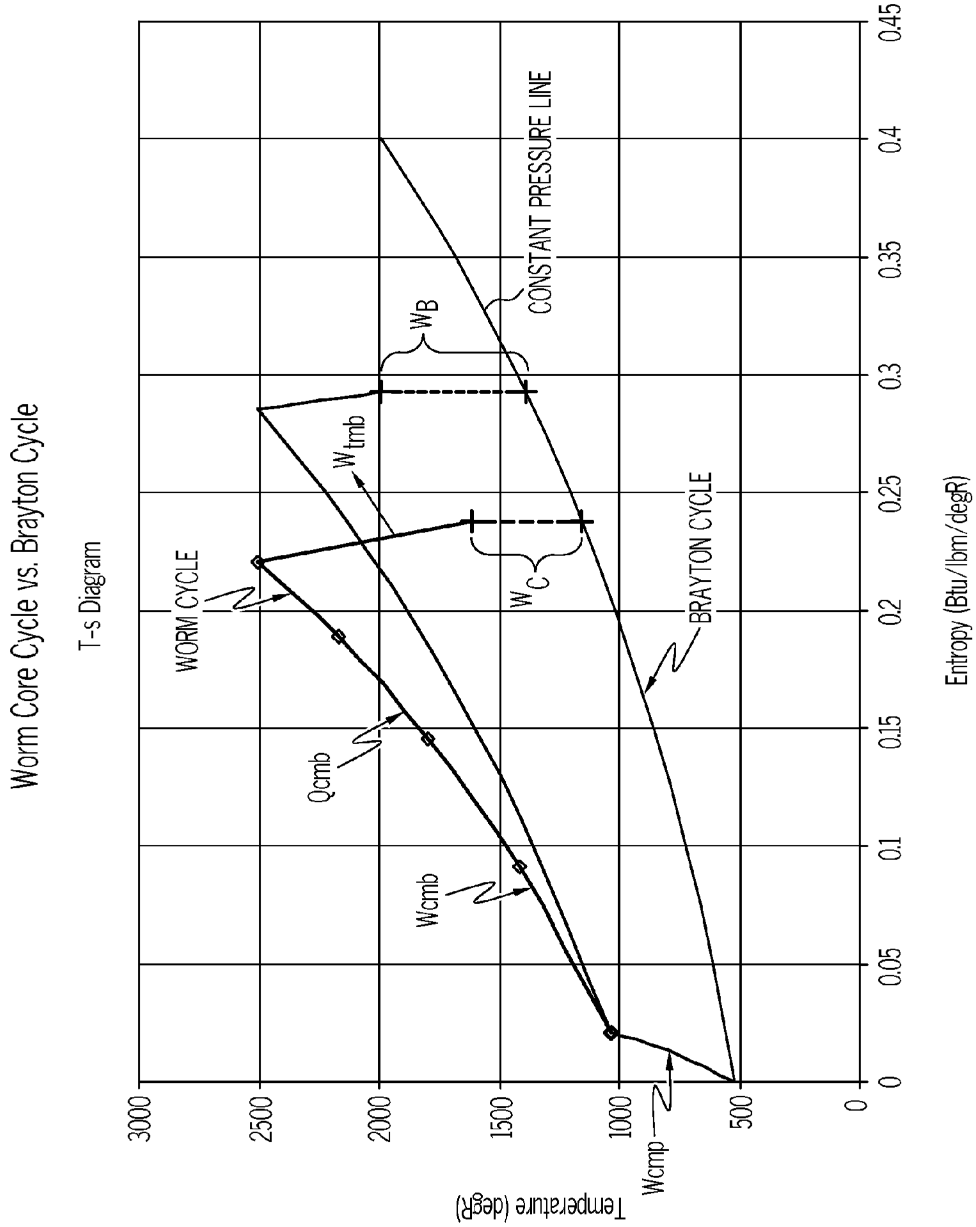

REAR PLANE
EXPANSION PLANE
COMPRESSION PLANE
FRONT FACE
DISCHARGE
EXPANSION
COMBUSTION
COMPRESSION
CAPTURE
AXIAL DEPTH
TIME
28
40
26
24
100

FIG. 11



Worm Core Cycle vs. Brayton Cycle
T-s Diagram
Temperature (degR)
Entropy (Btu/lbm/degR)
3000
2500
2000
1500
1000
500
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
WORM CYCLE
BRAYTON CYCLE
CONSTANT PRESSURE LINE
Qcmb
Wcmb
Wcmp
W_{tmb}
W_B
W_C

FIG. 12

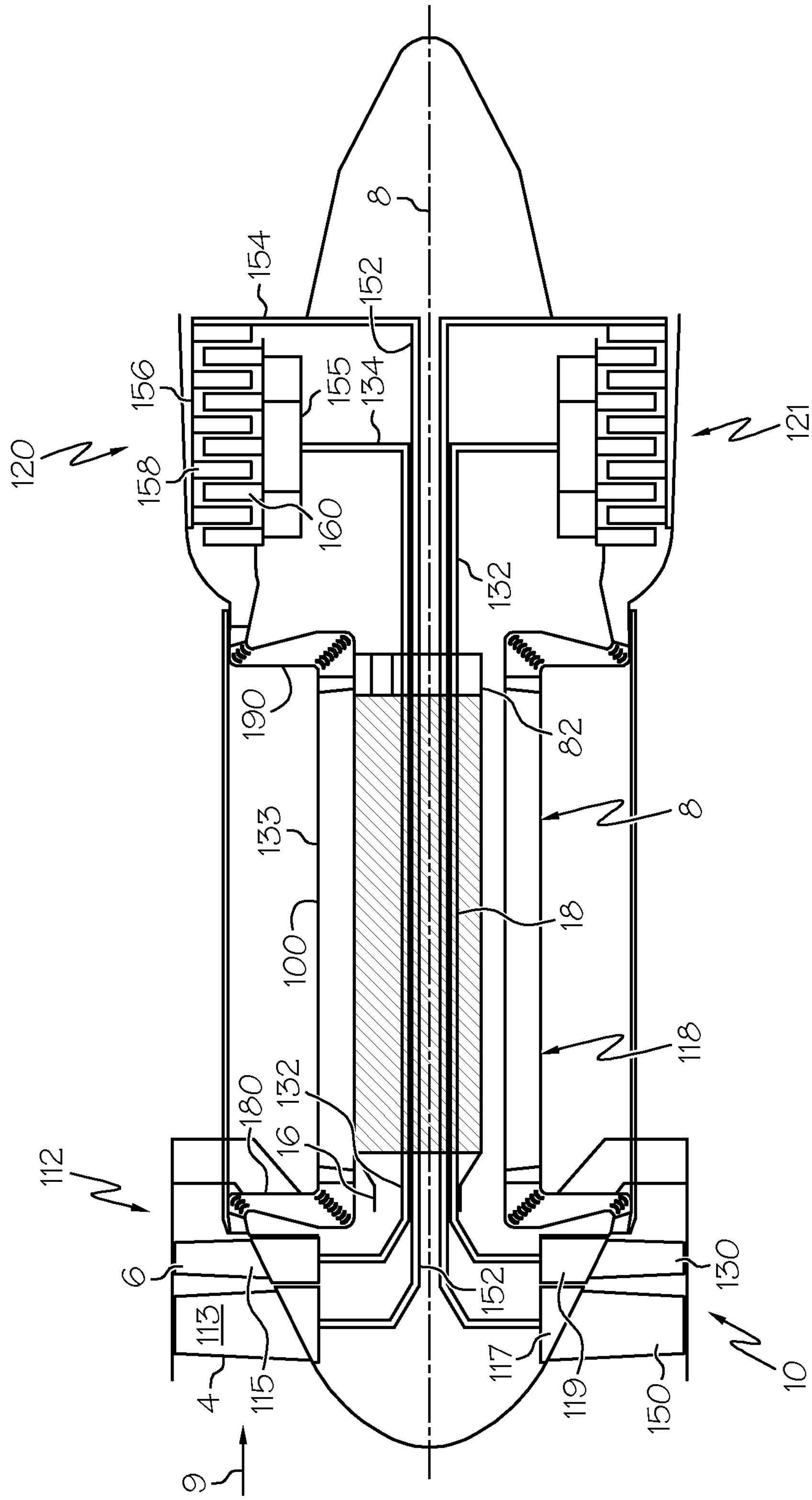

8
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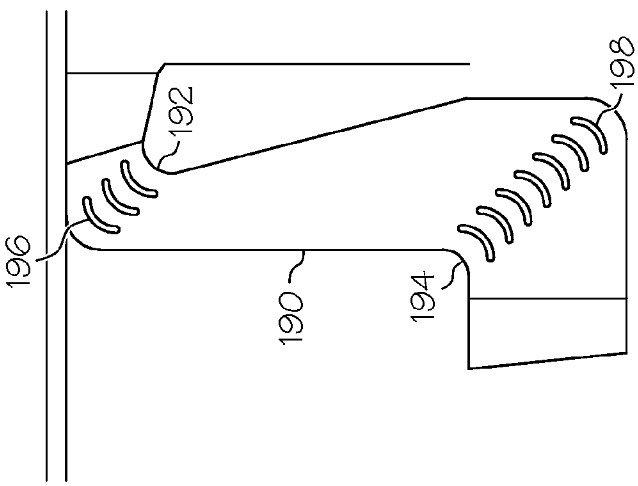
FIG. 13


190
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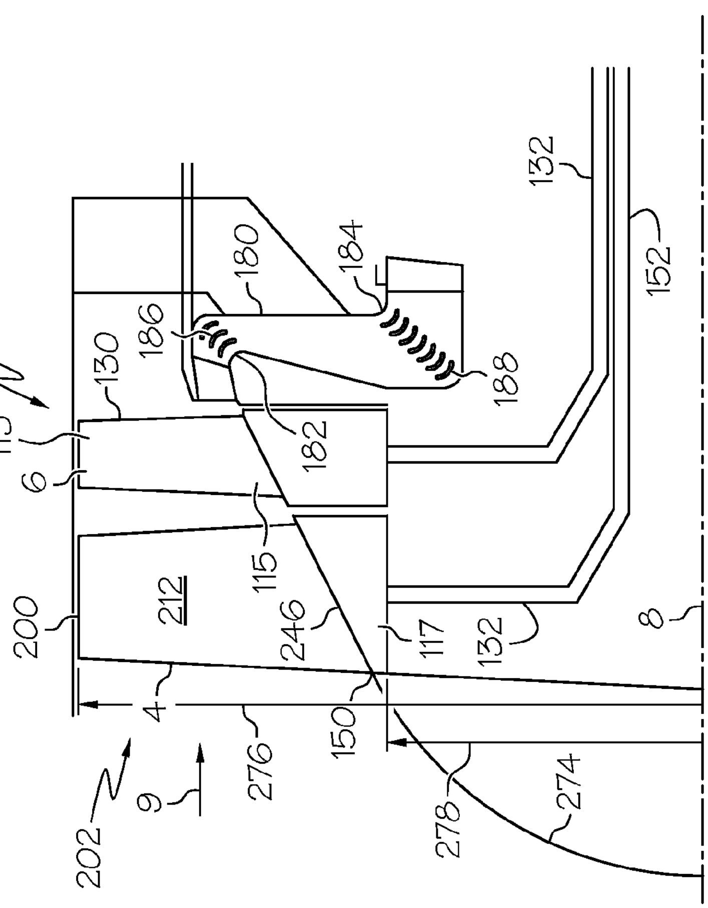
198

FIG. 15


112
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278
274

FIG. 14

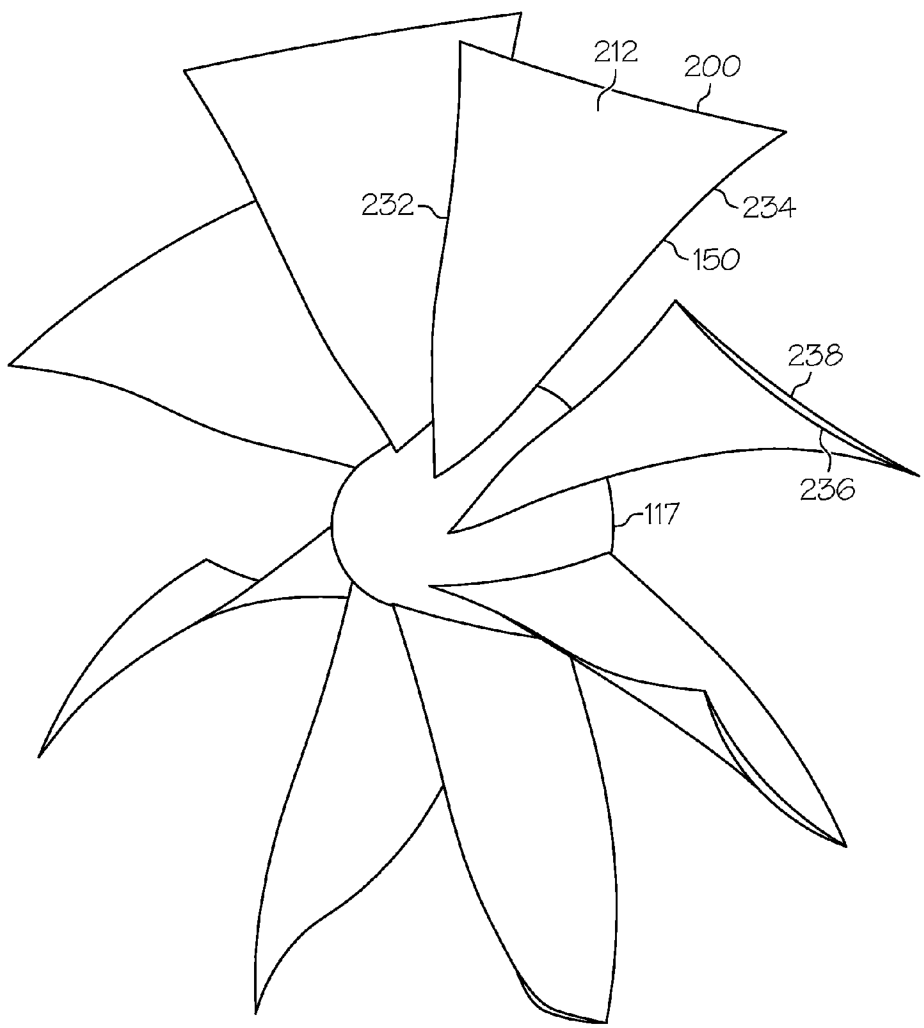

FIG. 16

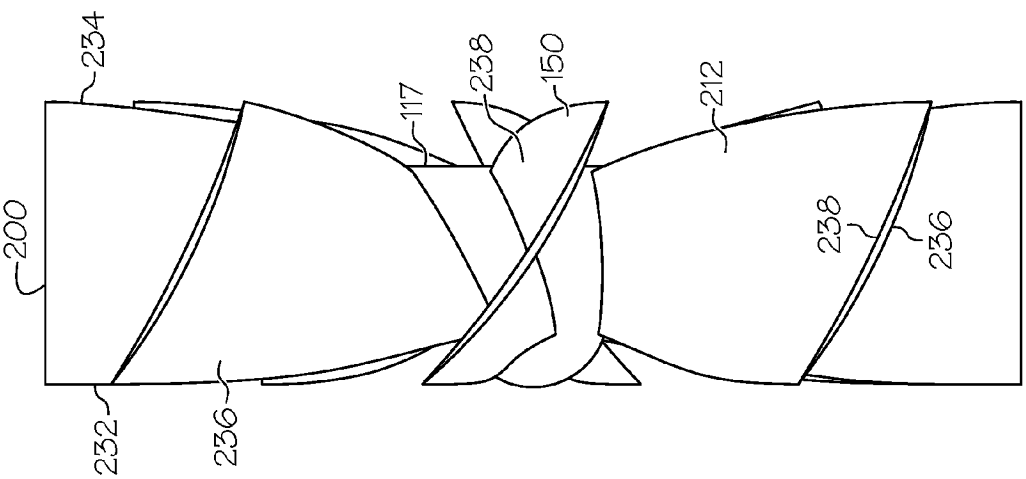

FIG. 18

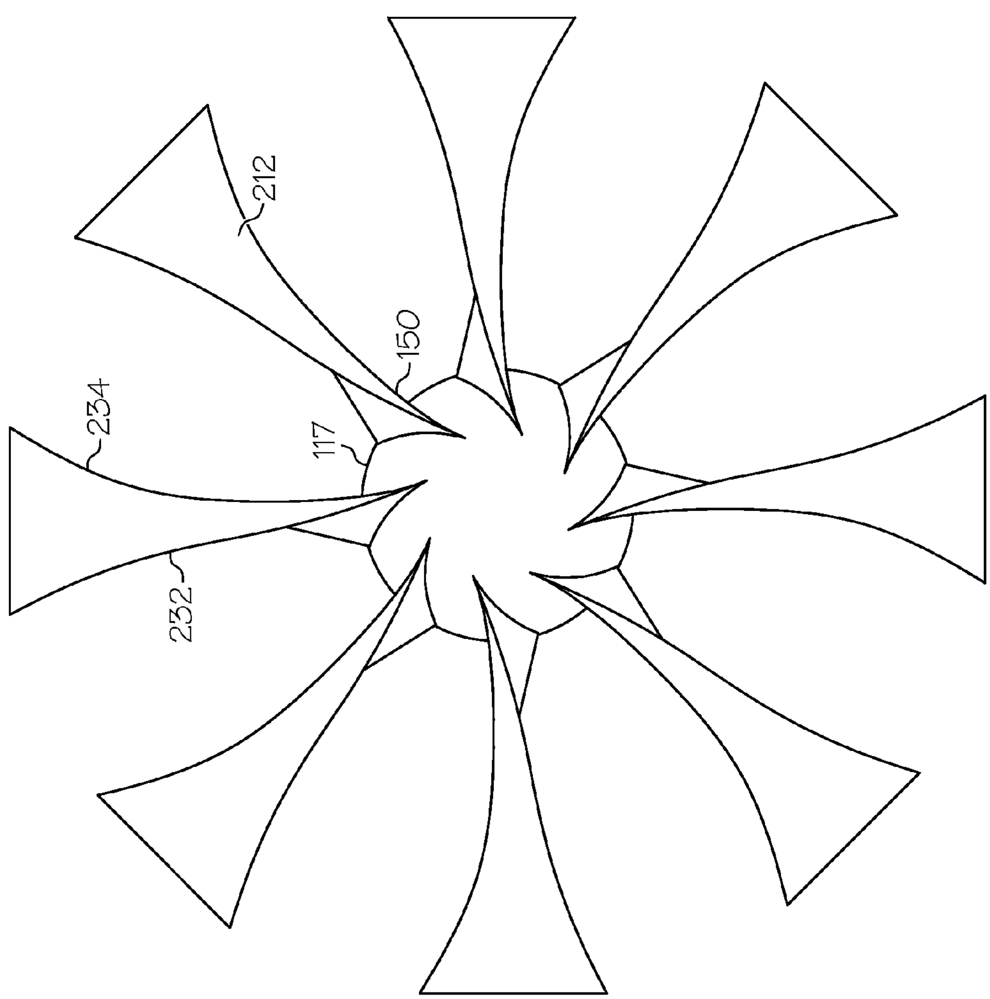

FIG. 17

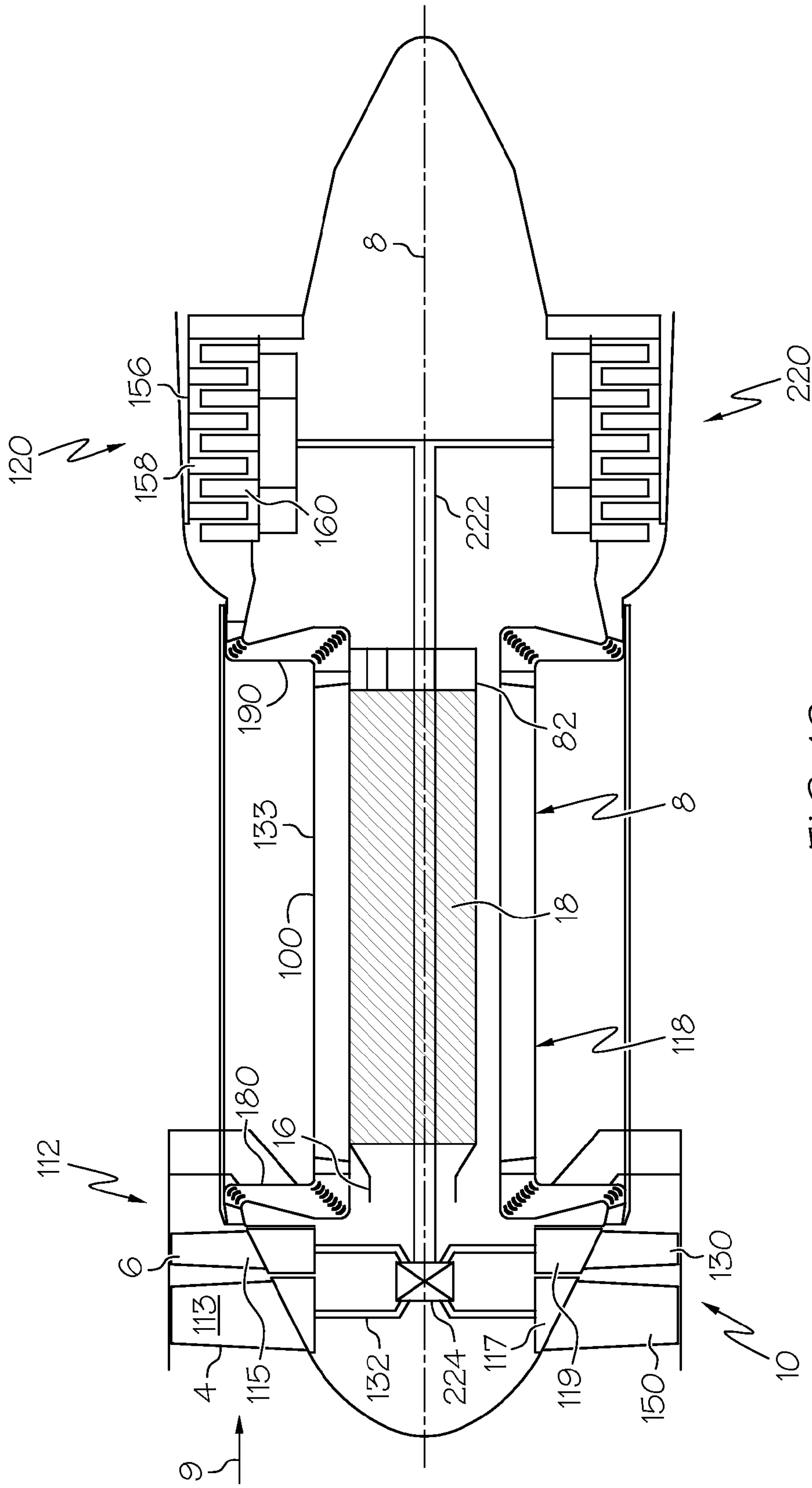

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FIG. 19

COUNTER-ROTATABLE FAN GAS TURBINE ENGINE WITH AXIAL FLOW POSITIVE DISPLACEMENT WORM GAS GENERATOR

The Government has rights to this invention pursuant to Contract No. NAS3-01135 awarded by the NASA.

BACKGROUND OF THE INVENTION

The present invention relates generally to gas turbine engines with counter-rotatable fans and, more particularly, to such engines having axial flow positive displacement gas generators and worm and screw compressors and turbines.

Aircraft gas turbine engines generally have in downstream flow relationship fan, compressor, combustion, and turbine sections. The turbine sections generally drive the compressor and fan sections. The combustor section burns fuel in an airflow compressed by the compressor to provide energy to the turbines. Aircraft gas turbine engines may have one, two, three, or more rotors or spools. One or two fans upstream of the compressor are driven by one or two turbines as are the compressors. The fans, compressors, and turbines typically include radially extending blades. Core engines or gas generators of the aircraft gas turbine engine generally include a high pressure compressor, a combustor, and a high pressure turbine to provide high energy fluid to the turbines to provide power for the engine's fan or fans. Continuous axial flow gas turbine engines are utilized in a wide range of applications owing in a great deal to a combination of desirable attributes such as high specific energy exhaust stream (energy per unit mass), high mass flow rate for a given frontal area, continuous near steady fluid flow, and reasonable efficiency over a wide range of operating conditions. It is desirable to have light-weight and highly efficient engines. One type of highly efficient engine includes counter-rotatable fans powered by counter-rotatable low pressure turbines such as those disclosed in U.S. Pat. Nos. 6,763,653, and 6,763,654.

Axial flow gas generators are particularly useful in many turbomachinery applications. Turbomachinery based gas generators are utilized in a wide range of applications owing in a great deal to a combination of desirable attributes such as high specific energy exhaust stream (energy per unit mass), high mass flow rate for a given frontal area, continuous, near steady fluid flow, reasonable thermal efficiency over a wide range of operating conditions. It is a goal of gas turbine engine manufacturers to have light-weight and highly efficient engines and gas generators. It is another goal to have as few parts as possible in the gas generator to reduce the costs of manufacturing, installing, refurbishing, overhauling, and replacing the gas generator. Therefore, it is desirable to have an aircraft gas turbine engine with a gas generator that improves all of these characteristics of gas turbine engines and their gas generators.

BRIEF DESCRIPTION OF THE INVENTION

A counter-rotatable fan gas turbine engine includes in downstream serial flow relationship, a counter-rotatable fan section, a positive displacement axial flow or worm gas generator, and a low pressure turbine operably connected to the counter-rotatable fan section. In one embodiment of the engine, the low pressure turbine is a counter-rotatable low pressure turbine. The positive displacement axial flow gas generator, includes an inlet axially spaced apart and upstream from an outlet. Inner and outer bodies having offset inner and outer axes, respectively, extend from the inlet to the outlet. Either or both bodies may be rotatable. In one embodiment of the generator, the inner body is rotatable about the inner axis within the outer body. The outer body may be rotatably fixed or rotatable about the outer axis. The inner and outer bodies have intermeshed inner and outer helical blades wound about inner and outer axes, respectively. The inner and outer helical blades extend radially outwardly and inwardly, respectively.

The helical blades have first, second, and third twist slopes in the first, second, and third sections, respectively. A twist slope is defined as the amount of rotation of a cross-section of the helical element per unit distance along an axis. The first twist slopes are less than the second twist slopes and the third twist slopes are less than the second twist slopes. A combustion section extends axially downstream from the end of the first section through at least a portion of the second section.

One exemplary embodiment of the counter-rotatable low pressure turbine includes upstream and downstream low pressure turbines drivingly connected to counter-rotatable upstream and downstream fan stages in the counter-rotatable fan section. A more particular embodiment of the counter-rotatable fan gas turbine engine includes the downstream low pressure turbine drivingly connected to the upstream fan stage by a low pressure inner shaft and the upstream low pressure turbine drivingly connected to the downstream fan stage by a low pressure outer shaft.

Another exemplary embodiment of the counter-rotatable low pressure turbine includes annular low pressure inner and outer drums drivingly connected to counter-rotatable upstream and downstream fan stages in the counter-rotatable fan section. The inner drum includes a plurality of axially spaced apart rows of circumferentially spaced apart and radially outwardly extending turbine blades. The outer drum includes a plurality of axially spaced apart rows of circumferentially spaced apart and radially inwardly extending turbine blades. The radially inwardly extending turbine blades are interdigitated with the radially outwardly extending turbine blades. A more particular embodiment of the counter-rotatable fan gas turbine engine includes the annular low pressure inner drum being drivingly connected to the downstream fan stage by a low pressure outer shaft and the outer drum being drivingly connected to the upstream fan stage by a low pressure inner shaft.

In another embodiment of the engine, the low pressure turbine is a single direction of rotation turbine drivingly connected to the counter-rotatable fan section by a single low pressure shaft through a drive gearbox such as a planetary gear box.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross-sectional view illustration of an exemplary aircraft gas turbine engine with a counter-rotatable fan section and a positive displacement axial flow or worm gas generator.

FIG. **2** is a diagrammatic cross-sectional view illustration of the gas generator illustrated in FIG. **1**.

FIG. **3** is a diagrammatic partially cut away perspective view illustration of helical portions of inner and outer bodies of the gas generator illustrated in FIG. **2**.

FIG. **4** is a diagrammatic cross-sectional view illustration of gearing between inner and outer bodies of the gas generator illustrated in FIG. **3**.

FIG. **5** is a diagrammatic cut away perspective view illustration of the helical portions of inner and outer bodies of the gas generator illustrated in FIG. **3**.

FIG. **6** is a diagrammatic cross-sectional view illustration of the inner and outer bodies taken through **6-6** in FIG. **4**.

FIGS. **7-10** are diagrammatic cross-sectional view illustrations of an alternate inner and outer body configuration at different inner body relative angular positions.

FIG. **11** is a diagrammatic cross-sectional view illustration of a positive displacement gas generator having the inner and outer bodies illustrated in FIG. **7**.

FIG. **12** is a diagrammatic view illustration of a T S temperature-entropy diagram illustrating a cycle of the gas generator illustrated in FIG. **2**.

FIG. **13** is a cross-sectional view illustration of an alternative exemplary aircraft gas turbine engine with a counter-rotatable fan section and a positive displacement axial flow or worm gas generator and two interdigitated low pressure turbines.

FIG. **14** is a cross-sectional view illustration of a short inlet transition duct between a fan section containing the counter-rotatable fans to the worm gas generator illustrated in FIG. **1**.

FIG. **15** is a cross-sectional view illustration of a short outlet transition duct from the worm gas generator to counter-rotatable low pressure turbines illustrated in FIG. **1**.

FIG. **16** is a perspective view illustration of an upstream fan stage of the counter-rotatable fans illustrated in FIG. **1**.

FIG. **17** is a forward looking aft perspective view illustration of the upstream fan stage of the counter-rotatable fans illustrated in FIG. **16**.

FIG. **18** is a side perspective view illustration of the upstream fan stage of the counter-rotatable fans illustrated in FIG. **16**.

FIG. **19** is a cross-sectional view illustration of an alternative exemplary aircraft gas turbine engine with counter-rotatable fan section and a positive displacement axial flow or worm gas generator and a single direction of rotation turbine drivingly connected to the counter-rotatable fan section.

DETAILED DESCRIPTION OF THE INVENTION

Illustrated in FIG. **1** is an exemplary embodiment of an axial flow positive displacement or worm gas generator **100** in a counter-rotatable fan gas turbine engine **10** circumscribed about an engine centerline **8**. A counter-rotatable fan section **112** of the engine **10** includes counter-rotatable upstream and downstream fan stages **4**, **6** (further illustrated in FIGS. **16-18**) and receives inlet airflow of ambient air **9**. The upstream and downstream fan stages **4**, **6** include upstream and downstream fan blade rows **113**, **115**, mounted on upstream and downstream fan disks **117**, **119**, respectively. Downstream of the fan section **112** is a core engine **118** which is the worm gas generator **100**.

The worm gas generator **100** discharges hot gases into a low pressure turbine (LPT) **120** which powers the counter-rotatable upstream and downstream fan stages **4**, **6**. The low pressure turbine (LPT) **120** illustrated in FIGS. **1** and **13** is a counter-rotatable low pressure turbine (LPT) **121**. The worm gas generator **100** is substantially a high pressure spool **133**. The counter-rotatable LPT **121** is powered by the hot gases discharged by the worm gas generator **100** into the counter-rotatable LPT **121**. As illustrated in FIG. **1**, the counter-rotatable LPT **121** has, in serial downstream flow relationship, upstream and downstream low pressure turbines **122**, **124** respectively. The downstream low pressure turbine **124** is downstream of the upstream low pressure turbine **122**. Combustion gases are discharged from the gas generator **100** into the upstream low pressure turbine **122** having a row of upstream low pressure turbine blades **126**. The upstream low pressure turbine blades **126** are drivingly attached to downstream fan blades **130** of the downstream fan blade row **115** of the downstream fan stage **6** by a low pressure outer shaft **132** to form a low pressure outer spool **134** circumscribing the engine centerline **8**.

Combustion gases are discharged from the upstream low pressure turbine **122** into the downstream low pressure turbine **124** having a row of downstream low pressure turbine blades **142**. The downstream low pressure turbine blades **142** are drivingly attached to the upstream fan blade row **113** of upstream fan blades **150** of the upstream fan stage **4** by a low pressure inner shaft **152** to form a low pressure inner spool **154** circumscribing the engine centerline **8**. Thus, the downstream low pressure turbine **124** is drivingly connected to the upstream fan stage **4** by the low pressure inner shaft **152** and the upstream low pressure turbine **122** is drivingly connected to the downstream fan stage **6** by a low pressure outer shaft **132**.

An alternative embodiment of the counter-rotatable low pressure turbine (LPT) **121** is illustrated in FIG. **13**. The counter-rotatable low pressure turbine **121** illustrated in FIG. **13** includes an annular outer drum **156** drivingly connected to the upstream fan stage **4** by a low pressure inner shaft **152**. The outer drum **156** includes a plurality of axially spaced apart rows of circumferentially spaced apart and radially inwardly extending turbine blades **158**. The counter-rotatable low pressure turbine **121** also includes an annular low pressure inner drum **155** drivingly connected to the downstream fan stage **6** by a low pressure outer shaft **132**. The inner drum **155** includes a plurality of axially spaced apart rows of circumferentially spaced apart and radially outwardly extending turbine blades **160**. The radially inwardly extending turbine blades **158** are interdigitated with the radially outwardly extending turbine blades **160**.

The low pressure outer shaft **132** drivingly connects the inner drum **155** to the downstream fan blade row **115**. The low pressure outer shaft **132**, the inner drum **155**, and the downstream fan blade row **115** are major components of the low pressure outer spool **134**. The low pressure inner shaft **152** drivingly connects the outer drum **156** to the upstream fan blade row **113**. The low pressure inner shaft **152**, the outer drum **156**, and the upstream fan blade row **113** are major components of the low pressure inner spool **154**.

Referring to FIGS. **2-5**, the gas generator **100** includes a core assembly **15** having inner and outer bodies **12** and **14** extending from an inlet **20** to an outlet **22**. The inner body **12** is disposed within a cavity **19** of the outer body **14**. The inner and outer bodies **12**, **14** have inner and outer axes **16**, **18** respectively. The core assembly **15** has first, second, and third sections **24**, **26**, **28** in serial downstream flow relationship. A combustion section **40** extends axially downstream through at least a portion of the second section. As illustrated herein, the combustion section **40** extends axially downstream from the end of the first section **24** through the entire second section **26**. The core assembly **15** has continuous flow through the inlet **20** and the outlet **22**.

Individual charges of air **50** are captured in and by the first section **24**. Compression of the charges **50** occurs as the charges **50** pass from the first section **24** to the second section **26**. Thus, an entire charge **50** undergoes compression while it is in both the first and second sections **24**, **26**, respectively. Combustion begins in the second section **26** after the entire charge **50** has passed out of the first section **24** into the second section **26**. The third section **28** is an expansion section and, thus, extracts energy from the combusted charges of air **50** to power the first and second sections **24**, **26**, respectively. Expansion of the charges **50** occurs as the charges **50** pass from the second section **26** to the third section **28**. Thus, the

entire charge **50** undergoes expansion while it is in both the second and third sections **26**, **28**.

Either or both bodies may be rotatable and, if both bodies are rotatable, they rotate in the same circumferential direction clockwise or counter-clockwise at different rotational speeds determined by a fixed relationship. If only one body is rotatable, then the other body is fixed. In one embodiment of the generator, the inner body **12** is rotatable about the inner axis **16** within the outer body **14** and the outer body **14** may be rotatably fixed or rotatable about the outer axis **18**.

The inner and outer bodies **12**, **14** have intermeshed inner and outer helical elements wound about the inner and outer axes **16**, **18**, respectively. The elements are inner and outer helical blades **17**, **27** having inner and outer helical surfaces **21**, **23**, respectively. The term worm is used because it is commonly used to describe worm or screw compressors and is descriptive of the helical elements wound about the inner and outer axes **16**, **18**. The inner helical blades **17** extend radially outwardly from a hollow inner hub **51** of the inner body **12** and the outer helical blades **27** extend radially inwardly from an outer shell **53** of the outer body **14**. An inner helical edge **47** along the inner helical blade **17** sealingly engages the outer helical surface **23** of the outer helical blade **27** as they rotate relative to each other. An outer helical edge **48** along the outer helical blade **27** sealingly engages the inner helical surface **21** of the inner helical blade **17** as they rotate relative to each other.

Illustrated in FIG. **4** is a longitudinal cross-section taken through the inner and outer bodies **12**, **14**. The inner and outer bodies **12**, **14** are illustrated in axial cross-section in FIG. **6**. The inner body **12** is illustrated herein as having two inner body lobes **60** which correspond to two inner helical blades **17** and which results in a football or pointed oval-shaped inner body cross-section **69**. The outer body **14** has three outer body lobes **64** which corresponds to three outer helical blades **27** (illustrated in FIGS. **3** and **4**). Note that 3 sealing points **62** between the inner and outer bodies **12**, **14** are illustrated in FIG. **6** but that there is continuous sealing between the inner and outer helical blades **17**, **27** along the length of the inner and outer bodies **12**, **14**.

An alternative configuration of the inner and outer bodies **12**, **14** is illustrated in cross-section in FIGS. **7-10**. The inner body **12** is illustrated therein as having three inner body lobes **60** which correspond to three inner helical blades **17** which results in a triangularly-shaped inner body cross-section **68** as illustrated in FIG. **7**. The outer body **14** has two outer body lobes **64** which corresponds to two outer helical blades **27**. In general, if the inner body **12** has N number of lobes, the outer body **14** will have N+1 or N−1 lobes. Note that 5 sealing points **62** between the inner and outer bodies **12**, **14** are illustrated in FIG. **7** but that there is continuous sealing between the inner and outer helical blades **17**, **27** along the length of the inner and outer bodies **12**, **14**.

Referring to FIG. **5**, the helical elements have constant first, second, and third twist slopes **34**, **36**, **38** in the first, second, and third sections **24**, **26**, **28**, respectively. A twist slope A is defined as the amount of rotation of a cross-section **41** of the helical element (such as the oval-shaped or triangularly-shaped inner body cross-sections **69**, **68** illustrated in FIGS. **6** and **7**, respectively) per distance along an axis such as the inner axis **16** as illustrated in FIG. **5**. Illustrated in FIG. **5** is 360 degrees of rotation of the inner body cross-section **41**. The twist slope A is also 360 degrees or 2 Pi radians divided by an axial distance CD between two adjacent crests **44** along the same inner or outer helical edges **47**, **48** of the helical element such as the inner or outer helical blades **17**, **27** as illustrated in FIG. **5**. The axial distance CD is the distance of one full turn **43** of the helix.

The twist slope A of the inner element in each of the sections is different from the twist slope A of the outer element. The ratio of the twist slope A of the outer body **14** to the twist slope A of the inner body **12** is equal to the ratio of the number of inner helical blades **17** on the inner body **12** to the number of outer helical blades **27** blades on the outer body **14**. The first twist slopes **34** are less than the second twist slopes **36** and the third twist slopes **38** are less than the second twist slopes **36**. One might also describe the helical elements in terms of helical angle. The helical elements have constant first, second, and third helical angles corresponding to the constant first, second, and third twist slopes **34**, **36**, **38** in the first, second, and third sections **24**, **26**, **28**, respectively, in much the same way one would describe a screw in terms of pitch and pitch angle.

Referring again to FIGS. **3-5**, the inner helical blade **17** in the first section **24** has a sufficient number of turns **43** to trap the charges of air **50** in the first section **24** during the generator's operation. The trapped charges of air **50** allow positive displacement compression so that higher pressures developed downstream cannot force air or the charges back out the inlet **20**. In one embodiment of the gas generator, the number of turns **43** in the first section **24** is enough to mechanically trap the charges of air **50**. In another embodiment of the gas generator **100**, the number of turns **43** in the first section **24** is enough to dynamically trap the charges of air **50**. Mechanically trapped means that the charge **50** is trapped by being closed off from the inlet **20** at an upstream end **52** of the charge **50** before it passes into the second section **26** at a downstream end **54** of the charge **50**. Dynamically trapped means that though the downstream end **54** of the trapped charge may have passed into the second section **26**, the upstream end **52** of the charge has not yet completely closed. However, at its downstream end **54**, by the time a pressure wave from the second section travels to the inlet **20**, relative rotation between the bodies will have closed off the trapped charge of air **50** at its upstream end **52**.

For the fixed outer body **14** embodiment, the inner body **12** is cranked relative to the outer axis **18** so that as it rotates about the inner axis **16**, the inner axis **16** orbits about the outer axis **18** as illustrated in FIGS. **7-10**. The inner body **12** is illustrated as having been rotated about the inner axis **16** from its position in FIG. **7** to its position in FIG. **8**, and the inner axis **16** is illustrated as having orbited about the outer axis **18** about 90 degrees. The inner and outer bodies **12**, **14** are geared together so that they always rotate relative to each other at a fixed ratio as illustrated by gearing in coupling gearbox **82** in FIGS. **1** and **4**.

If the outer body **14** in FIG. **7** was not fixed, then it would rotate about the outer axis **18** at 1.5 times the rotational speed that the inner body **12** rotates about the inner axis **16**. The inner body **12** rotates about the inner axis **16** with an inner body rotational speed **74** equal to its orbital speed **76** divided by the number of inner body lobes. The number of inner lobes are equal to the number of blades. If the inner body **12** rotates in the same direction as its orbital direction, a 2 lobed outer body configuration is used. If the inner body **12** rotates in an opposite orbital direction, a 4 lobed outer body configuration is used.

The twist slopes of the outer body **14** are equal to the twist slopes of the inner body **12** times the number of inner body lobes N divided by the number of outer body lobes M. For the configuration illustrated in FIGS. **7-10** having three inner lobes or inner helical blades **17** and two outer lobes or outer

helical blades **27**, it takes 900 degrees of rotation of the outer body **14** and 600 degrees of rotation of the inner body **12** to mechanically capture one of the charges of air **50**. The inner body twist slope is substantially increased going from the first section **24** to the second section **26**. This axial location is designated the compression plane as indicated in FIG. **2**. Constant volume combustion is initiated in the second section **26** when the entire charge of air **50** crosses the compression plane and has passed entirely into the second section **26**. Each of the charges is combusted individually and, because the twist slopes in the inner and outer bodies remain constant through the second section **26**, there is constant volume combustion in the second section **26**. A further comparison to the embodiment of the inner and outer bodies **12**, **14** having two inner body lobes **60** (two inner helical blades **17**) may be had by comparing FIG. **11** to FIG. **2** particularly as regards the degrees of rotation of the outer body **14** and the degrees of rotation of the inner body **12** needed to capture one of the charges of air **50** and the difference in twist slopes of the first, second, and third sections **24**, **26**, and **28**.

Referring to FIGS. **2-4**, following the constant volume combustion in the second section **26**, the charge or working fluid undergoes a nearly isentropic expansion process in the third section **28** and work is extracted from the third section **28**. The expansion may be done at constant temperature. After the leading edge of the high temperature and high pressure charge crosses, the expansion plane, the volume of the charge of air **50** begins to expand and grow axially. This expansion extracts energy from the fluid, providing the work necessary to drive the first and second sections **24**, **26** and sustain the gas generating process. Following expansion, the fluid is discharged across the rear plane into a downstream plenum at substantially elevated temperature and pressure relative to its initial state.

FIG. **12** illustrates a temperature-entropy diagram (T-S diagram) of a cycle of the worm engine denoted as a worm core cycle versus a Brayton cycle. The worm core cycle inputs work into the compression stage of the cycle, denoted as Wcmp, for compression. The worm core cycle inputs work, denoted as Wcmb, into the constant volume combustion stage of the cycle and inputs heat, denoted as Qcmb, for combustion. The worm core cycle extracts work adiabatically, denoted as Wtmb, during the expansion stage of the cycle. The worm core cycle could extract work isothermally. In the exemplary embodiment of the worm core cycle engine illustrated herein, the third section **28** functions as a turbine of the engine centerline **8** and inputs work into both the first and second sections **24**, **26**.

Net work of the worm core cycle engine as illustrated in FIG. **12** is WC and the net work of the Brayton cycle is as WB. The net work of the worm cycle illustrated herein and Brayton cycles are referenced to inlet pressure of the engine centerline **8** indicated by a constant pressure line in FIG. **12**. The worm cycle illustrated herein also includes combustion through the entirety of the second section **26**. This cycle for a positive displacement engine or gas generator offers substantial performance benefits over Brayton cycle engines in terms of both net work and thermal efficiency. The ability to increase net work over that of the Brayton cycle will allow the same power requirement to be met with a smaller engine or gas generator, making the combination particularly attractive for weight and size sensitive applications.

Illustrated in FIGS. **1** and **13** and more particularly in FIG. **14** is a short inlet transition duct **180** between the fan section **112** and the core engine **118** or worm gas generator **100**. The short inlet transition duct **180** has two approximately 90 degree outer and inner inlet bends **182**, **184**. Annular outer and inner inlet turning vanes **186**, **188** disposed within the outer and inner inlet bends **182**, **184**, respectively, provide aerodynamically efficient flow through the bends. Illustrated in FIG. **15** is a short outlet transition duct **190** between the worm gas generator **100** and the counter-rotatable LPT **121**. The outlet transition duct **190** has two approximately 90 degree radially spaced apart bends denoted as outer and inner outlet bends **192**, **194**. Radially spaced apart annular outer and inner outlet turning vanes **196**, **198** disposed within the outer and inner outlet bends **192**, **194** provide aerodynamically efficient flow through the bends.

The upstream fan blades **150** are more specifically illustrated in FIGS. **14** and **16-18**. Each of the upstream fan blades **150** includes an airfoil **212** extending radially outwardly from the upstream fan disk **117** to a tip **200** of the airfoil **212**. The airfoil **212** includes a generally convex suction and concave pressure sides **236**, **238**, respectively, extending axially between leading and trailing edges **232** and **234**. The counter-rotatable upstream fan stage **4** is designed to have a low tip speed of about 850 ft/sec, a low inlet radius ratio that is in a range of about 0.10-0.15, and a high inlet design specific flow of about 44.5 lbs/sec. The low inlet radius ratio provides high flow per unit of frontal area.

Referring to FIG. **14**, the fan inlet radius ratio is defined as an inlet hub radius **278** divided by an inlet fan blade tip radius **276**. The inlet hub radius **278** and inlet fan blade tip radius **276** are measured with respect to the engine centerline **8**. The inlet fan blade tip radius **276** is measured from the centerline **8** and fan blade tips **200** at a fan inlet **202** to the fan section **112**. The inlet hub radius **278** is measured from the centerline **8** to an intersection of a hub **274** and fan blade platforms **246**.

The fan stages are illustrated as having ten upstream fan blades **150**. The downstream fan stage **6** is designed to have a tip speed consistent with its pressure ratio requirement as is appropriate for low noise and a conventional 0.3 class inlet radius ratio. The axial flow positive displacement gas generator **100** is a constant displacement high pressure spool with near constant pressure ratio independent of speed or inlet flow.

Illustrated in FIG. **19** is another embodiment of the engine **10** with the low pressure turbine **120** having a single direction of rotation turbine **220** drivingly connected to the counter-rotatable fan section **112** by a single low pressure shaft **222**. The low pressure shaft **222** is drivingly connected to the upstream and downstream fan blade rows **113**, **115** through a drive gearbox **224** such as a planetary gearbox.

While there have been described herein what are considered to be preferred and exemplary embodiments of the present invention, other modifications of the invention shall be apparent to those skilled in the art from the teachings herein and, it is therefore, desired to be secured in the appended claims all such modifications as fall within the true spirit and scope of the invention. Accordingly, what is desired to be secured by Letters Patent of the United States is the invention as defined and differentiated in the following claims.

What is claimed is:

1. A counter-rotatable fan gas turbine engine comprising:

in downstream serial flow relationship a counter-rotatable fan section, a worm gas generator, and a counter-rotatable low pressure turbine operably connected to the counter-rotatable fan section;

an inlet transition duct between the counter-rotatable fan section and the worm gas generator; and

radially spaced apart approximately 90 degree outer and inner inlet bends in the inlet transition duct.

2. The engine as claimed in claim 1 further comprising:

the gas generator including an inlet axially spaced apart and upstream from an outlet,

a core assembly including an inner body disposed within an outer body and the inner and outer bodies extending from the inlet to the outlet,

the inner and outer bodies having offset inner and outer axes respectively,

at least one of the inner and outer bodies being rotatable about a corresponding one of the inner and outer axes,

the inner and outer bodies having intermeshed inner and outer helical blades wound about the inner and outer axes respectively,

the inner and outer helical blades extending radially outwardly and inwardly respectively,

the core assembly having first, second, and third sections in serial downstream flow relationship extending between the inlet and the outlet,

the inner and outer helical blades having first, second, and third twist slopes in the first, second, and third sections respectively,

the first twist slopes being less than the second twist slopes and the third twist slopes being less than the second twist slopes, and

a combustor section extending axially downstream through at least a portion of the second section.

3. The engine as claimed in claim 2 further comprising the outer body being rotatable about the outer axis and the inner body and being rotatable about the inner axis.

4. The engine as claimed in claim 3 further comprising the inner and outer bodies being geared together in a fixed gear ratio.

5. The engine as claimed in claim 2 further comprising the outer body being rotatably fixed about the outer axis and the inner body being orbital about the outer axis.

6. The engine as claimed in claim 5 further comprising the inner and outer bodies being geared together in a fixed gear ratio.

7. The engine as claimed in claim 1 further comprising the counter-rotatable low pressure turbine including upstream and downstream low pressure turbines.

8. The engine as claimed in claim 7 further comprising:

the gas generator including an inlet axially spaced apart and upstream from an outlet,

a core assembly including an inner body disposed within an outer body and the inner and outer bodies extending from the inlet to the outlet,

the inner and outer bodies having offset inner and outer axes respectively,

at least one of the inner and outer bodies being rotatable about a corresponding one of the inner and outer axes,

the inner and outer bodies having intermeshed inner and outer helical blades wound about the inner and outer axes respectively,

the inner and outer helical blades extending radially outwardly and inwardly respectively,

the core assembly having first, second, and third sections in serial downstream flow relationship extending between the inlet and the outlet,

the inner and outer helical blades having first, second, and third twist slopes in the first, second, and third sections respectively,

the first twist slopes being less than the second twist slopes and the third twist slopes being less than the second twist slopes, and

a combustor section extending axially downstream through at least a portion of the second section.

9. The engine as claimed in claim 8 further comprising the outer body being rotatable about the outer axis and the inner body and being rotatable about the inner axis.

10. The engine as claimed in claim 9 further comprising the inner and outer bodies being geared together in a fixed gear ratio.

11. The engine as claimed in claim 8 further comprising the outer body being rotatably fixed about the outer axis and the inner body being orbital about the outer axis.

12. The engine as claimed in claim 11 further comprising the inner and outer bodies being geared together in a fixed gear ratio.

13. The engine as claimed in claim 7 further comprising upstream and downstream low pressure turbines in the counter-rotatable low pressure turbine drivingly connected to counter-rotatable upstream and downstream fan stages in the counter-rotatable fan section.

14. The engine as claimed in claim 13 further comprising the downstream low pressure turbine drivingly connected to the upstream fan stage by a low pressure inner shaft and the upstream low pressure turbine drivingly connected to the downstream fan stage by a low pressure outer shaft.

15. The engine as claimed in claim 14 further comprising:

the gas generator including an inlet axially spaced apart and upstream from an outlet,

a core assembly including an inner body disposed within an outer body and the inner and outer bodies extending from the inlet to the outlet,

the inner and outer bodies having offset inner and outer axes respectively,

at least one of the inner and outer bodies being rotatable about a corresponding one of the inner and outer axes,

the inner and outer bodies having intermeshed inner and outer helical blades wound about the inner and outer axes respectively,

the inner and outer helical blades extending radially outwardly and inwardly respectively,

the core assembly having first, second, and third sections in serial downstream flow relationship extending between the inlet and the outlet,

the inner and outer helical blades having first, second, and third twist slopes in the first, second, and third sections respectively,

the first twist slopes being less than the second twist slopes and the third twist slopes being less than the second twist slopes, and

a combustor section extending axially downstream through at least a portion of the second section.

16. The engine as claimed in claim 15 further comprising the outer body being rotatable about the outer axis and the inner body and being rotatable about the inner axis.

17. The engine as claimed in claim 16 further comprising the inner and outer bodies being geared together in a fixed gear ratio.

18. The engine as claimed in claim 15 further comprising the outer body being rotatably fixed about the outer axis and the inner body being orbital about the outer axis.

19. The engine as claimed in claim 18 further comprising the inner and outer bodies being geared together in a fixed gear ratio.

20. The engine as claimed in claim 7 further comprising:

annular low pressure inner and outer drums in the counter-rotatable low pressure turbine drivingly connected to counter-rotatable upstream and downstream fan stages in the counter-rotatable fan section,

a plurality of axially spaced apart rows of circumferentially spaced apart and radially outwardly extending turbine blades of the inner drum,

a plurality of axially spaced apart rows of circumferentially spaced apart and radially inwardly extending turbine blades of the outer drum, and

the radially inwardly extending turbine blades being interdigitated with the radially outwardly extending turbine blades.

21. The engine as claimed in claim **20** further comprising the annular low pressure inner drum drivingly connected to the downstream fan stage by a low pressure outer shaft and the outer drum drivingly connected to the upstream fan stage by a low pressure inner shaft.

22. The engine as claimed in claim **20** further comprising:

the gas generator including an inlet axially spaced apart and upstream from an outlet,

a core assembly including an inner body disposed within an outer body and the inner and outer bodies extending from the inlet to the outlet,

the inner and outer bodies having offset inner and outer axes respectively,

at least one of the inner and outer bodies being rotatable about a corresponding one of the inner and outer axes,

the inner and outer bodies having intermeshed inner and outer helical blades wound about the inner and outer axes respectively,

the inner and outer helical blades extending radially outwardly and inwardly respectively,

the core assembly having first, second, and third sections in serial downstream flow relationship extending between the inlet and the outlet,

the inner and outer helical blades having first, second, and third twist slopes in the first, second, and third sections respectively,

the first twist slopes being less than the second twist slopes and the third twist slopes being less than the second twist slopes, and

a combustor section extending axially downstream through at least a portion of the second section.

23. The engine as claimed in claim **22** further comprising the outer body being rotatable about the outer axis and the inner body and being rotatable about the inner axis.

24. The engine as claimed in claim **23** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

25. The engine as claimed in claim **22** further comprising the outer body being rotatably fixed about the outer axis and the inner body being orbital about the outer axis.

26. The engine as claimed in claim **25** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

27. The engine as claimed in claim **1** further comprising counter-rotatable upstream and downstream fan stages having upstream and downstream low inlet radius ratios respectively in a range of about 0.10-0.15.

28. The engine as claimed in claim **27** further comprising:

the gas generator including an inlet axially spaced apart and upstream from an outlet,

a core assembly including an inner body disposed within an outer body and the inner and outer bodies extending from the inlet to the outlet,

the inner and outer bodies having offset inner and outer axes respectively,

at least one of the inner and outer bodies being rotatable about a corresponding one of the inner and outer axes,

the inner and outer bodies having intermeshed inner and outer helical blades wound about the inner and outer axes respectively,

the inner and outer helical blades extending radially outwardly and inwardly respectively,

the core assembly having first, second, and third sections in serial downstream flow relationship extending between the inlet and the outlet,

the inner and outer helical blades having first, second, and third twist slopes in the first, second, and third sections respectively,

the first twist slopes being less than the second twist slopes and the third twist slopes being less than the second twist slopes, and

a combustor section extending axially downstream through at least a portion of the second section.

29. The engine as claimed in claim **28** further comprising the outer body being rotatable about the outer axis and the inner body and being rotatable about the inner axis.

30. The engine as claimed in claim **29** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

31. The engine as claimed in claim **28** further comprising the outer body being rotatably fixed about the outer axis and the inner body being orbital about the outer axis.

32. The engine as claimed in claim **31** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

33. A counter-rotatable fan gas turbine engine comprising:

in downstream serial flow relationship a counter-rotatable fan section, a worm gas generator, and a counter-rotatable low pressure turbine operably connected to the counter-rotatable fan section,

an inlet transition duct between the counter-rotatable fan section and the worm gas generator, radially spaced apart outer and inner inlet bends in the inlet transition duct, and

radially spaced apart annular outer and inner inlet turning vanes disposed within the outer and inner inlet bends respectively.

34. The engine as claimed in claim **33** further comprising:

an outlet transition duct between the worm gas generator and the counter-rotatable low pressure turbine,

radially spaced apart outer and inner outlet bends in the outlet transition duct, and

radially spaced apart annular outer and inner outlet turning vanes disposed within the outer and inner outlet bends respectively.

35. The engine as claimed in claim **34** further comprising:

the gas generator including an inlet axially spaced apart and upstream from an outlet,

a core assembly including an inner body disposed within an outer body and the inner and outer bodies extending from the inlet to the outlet,

the inner and outer bodies having offset inner and outer axes respectively,

at least one of the inner and outer bodies being rotatable about a corresponding one of the inner and outer axes,

the inner and outer bodies having intermeshed inner and outer helical blades wound about the inner and outer axes respectively,

the inner and outer helical blades extending radially outwardly and inwardly respectively,

the core assembly having first, second, and third sections in serial downstream flow relationship extending between the inlet and the outlet,

the inner and outer helical blades having first, second, and third twist slopes in the first, second, and third sections respectively,

the first twist slopes being less than the second twist slopes and the third twist slopes being less than the second twist slopes, and

a combustor section extending axially downstream through at least a portion of the second section.

36. The engine as claimed in claim **35** further comprising the outer body being rotatable about the outer axis and the inner body and being rotatable about the inner axis.

37. The engine as claimed in claim **36** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

38. The engine as claimed in claim **35** further comprising the outer body being rotatably fixed about the outer axis and the inner body being orbital about the outer axis.

39. The engine as claimed in claim **38** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

40. A counter-rotatable fan gas turbine engine comprising:

in downstream serial flow relationship a counter-rotatable fan section, a worm gas generator, and a counter-rotatable low pressure turbine operably connected to the counter-rotatable fan section,

counter-rotatable upstream and downstream fan stages having upstream and downstream low inlet radius ratios respectively in a range of about 0.10-0.15,

an inlet transition duct between the counter-rotatable fan section and the worm gas generator,

radially spaced apart outer and inner inlet bends in the inlet transition duct,

radially spaced apart annular outer and inner inlet turning vanes disposed within the outer and inner inlet bends respectively,

an outlet transition duct between the worm gas generator and the counter-rotatable low pressure turbine,

radially spaced apart outer and inner outlet bends in the outlet transition duct, and

radially spaced apart annular outer and inner outlet turning vanes disposed within the outer and inner outlet bends respectively.

41. The engine as claimed in claim **40** further comprising:

the gas generator including an inlet axially spaced apart and upstream from an outlet,

a core assembly including an inner body disposed within an outer body and the inner and outer bodies extending from the inlet to the outlet,

the inner and outer bodies having offset inner and outer axes respectively,

at least one of the inner and outer bodies being rotatable about a corresponding one of the inner and outer axes,

the inner and outer bodies having intermeshed inner and outer helical blades wound about the inner and outer axes respectively,

the inner and outer helical blades extending radially outwardly and inwardly respectively,

the core assembly having first, second, and third sections in serial downstream flow relationship extending between the inlet and the outlet,

the inner and outer helical blades having first, second, and third twist slopes in the first, second, and third sections respectively,

the first twist slopes being less than the second twist slopes and the third twist slopes being less than the second twist slopes, and

a combustor section extending axially downstream through at least a portion of the second section.

42. The engine as claimed in claim **41** further comprising the outer body being rotatable about the outer axis and the inner body and being rotatable about the inner axis.

43. The engine as claimed in claim **42** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

44. The engine as claimed in claim **41** further comprising the outer body being rotatably fixed about the outer axis and the inner body being orbital about the outer axis.

45. The engine as claimed in claim **44** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

46. A counter-rotatable fan gas turbine engine comprising:

in downstream serial flow relationship a counter-rotatable fan section, a worm gas generator, and a low pressure turbine operably connected to the counter-rotatable fan section;

an inlet transition duct between the counter-rotatable fan section and the worm gas generator; and

radially spaced apart approximately 90 degree outer and inner inlet bends in the inlet transition duct.

47. The engine as claimed in claim **46** further comprising the low pressure turbine being a single direction of rotation turbine drivingly connected to the counter-rotatable fan section by a single low pressure shaft through a drive gearbox.

48. The engine as claimed in claim **47** further comprising:

the gas generator including an inlet axially spaced apart and upstream from an outlet,

a core assembly including an inner body disposed within an outer body and the inner and outer bodies extending from the inlet to the outlet,

the inner and outer bodies having offset inner and outer axes respectively,

at least one of the inner and outer bodies being rotatable about a corresponding one of the inner and outer axes,

the inner and outer bodies having intermeshed inner and outer helical blades wound about the inner and outer axes respectively,

the inner and outer helical blades extending radially outwardly and inwardly respectively,

the core assembly having first, second, and third sections in serial downstream flow relationship extending between the inlet and the outlet,

the inner and outer helical blades having first, second, and third twist slopes in the first, second, and third sections respectively,

the first twist slopes being less than the second twist slopes and the third twist slopes being less than the second twist slopes, and

a combustor section extending axially downstream through at least a portion of the second section.

49. The engine as claimed in claim **48** further comprising the outer body being rotatable about the outer axis and the inner body and being rotatable about the inner axis.

50. The engine as claimed in claim **49** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

51. The engine as claimed in claim **48** further comprising the outer body being rotatably fixed about the outer axis and the inner body being orbital about the outer axis.

52. The engine as claimed in claim **51** further comprising the inner and outer bodies being geared together in a fixed gear ratio.

53. A counter-rotatable fan gas turbine engine comprising: in downstream serial flow relationship a counter-rotatable fan section, a worm gas generator, and a low pressure turbine operably connected to the counter-rotatable fan section,

an inlet transition duct between the counter-rotatable fan section and the worm gas generator,

radially spaced apart outer and inner inlet bends in the inlet transition duct, and

radially spaced apart annular outer and inner inlet turning vanes disposed within the outer and inner inlet bends respectively.

54. The engine as claimed in claim **53** further comprising: an outlet transition duct between the worm gas generator and the low pressure turbine,

radially spaced apart outer and inner outlet bends in the outlet transition duct, and

radially spaced apart annular outer and inner outlet turning vanes disposed within the outer and inner outlet bends respectively.

55. A counter-rotatable fan gas turbine engine comprising: in downstream serial flow relationship a counter-rotatable fan section having counter-rotatable upstream and downstream fan stages, a worm gas generator, and a low pressure turbine operably connected to the counter-rotatable fan section;

an inlet transition duct between the counter-rotatable fan section and the worm gas generator;

radially spaced apart approximately 90 degree outer and inner inlet bends in the inlet transition duct;

the counter-rotatable upstream fan stage having a low inlet radius ratio in a range of about 0.10-0.15;

the fan inlet radius ratio being defined as an inlet hub radius divided by an inlet fan blade tip radius; and

the inlet hub radius and inlet fan blade tip radius being measured with respect to an engine centerline of the engine.

56. The engine as claimed in claim **55** further comprising the low pressure turbine being a single direction of rotation turbine drivingly connected to the counter-rotatable fan section by a single low pressure shaft through a drive gearbox.

57. The engine as claimed in claim **55** further comprising the low pressure turbine being a counter-rotatable low pressure turbine.

58. The engine as claimed in claim **57** further comprising upstream and downstream low pressure turbines in the counter-rotatable low pressure turbine drivingly connected to the counter-rotatable upstream and downstream fan stages in the counter-rotatable fan section.

59. The engine as claimed in claim **57** further comprising: annular low pressure inner and outer drums in the counter-rotatable low pressure turbine drivingly connected to counter-rotatable upstream and downstream fan stages in the counter-rotatable fan section,

a plurality of axially spaced apart rows of circumferentially spaced apart and radially outwardly extending turbine blades of the inner drum,

a plurality of axially spaced apart rows of circumferentially spaced apart and radially inwardly extending turbine blades of the outer drum, and

the radially inwardly extending turbine blades being interdigitated with the radially outwardly extending turbine blades.

60. The engine as claimed in claim **59** further comprising the annular low pressure inner drum drivingly connected to the downstream fan stage by a low pressure outer shaft and the outer drum drivingly connected to the upstream fan stage by a low pressure inner shaft.

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